Where does the water come from?

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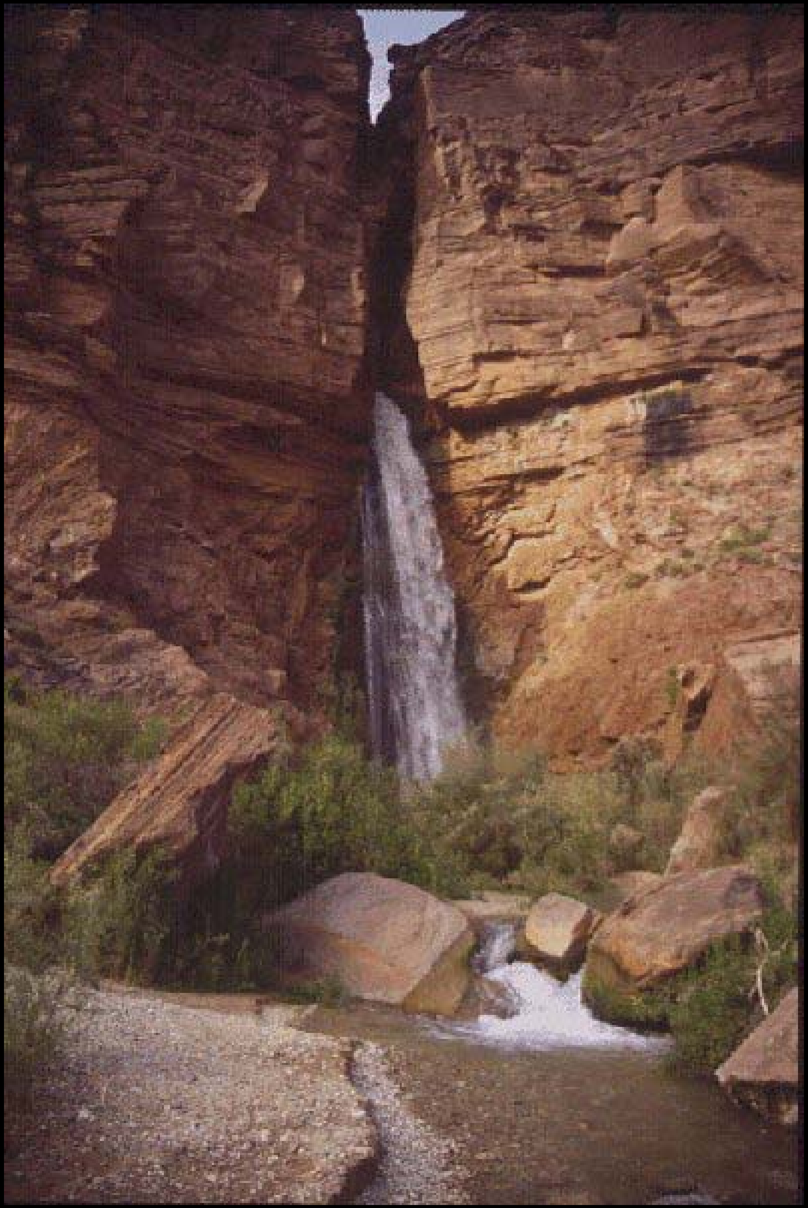
Part I. Where did Earth acquire its water?

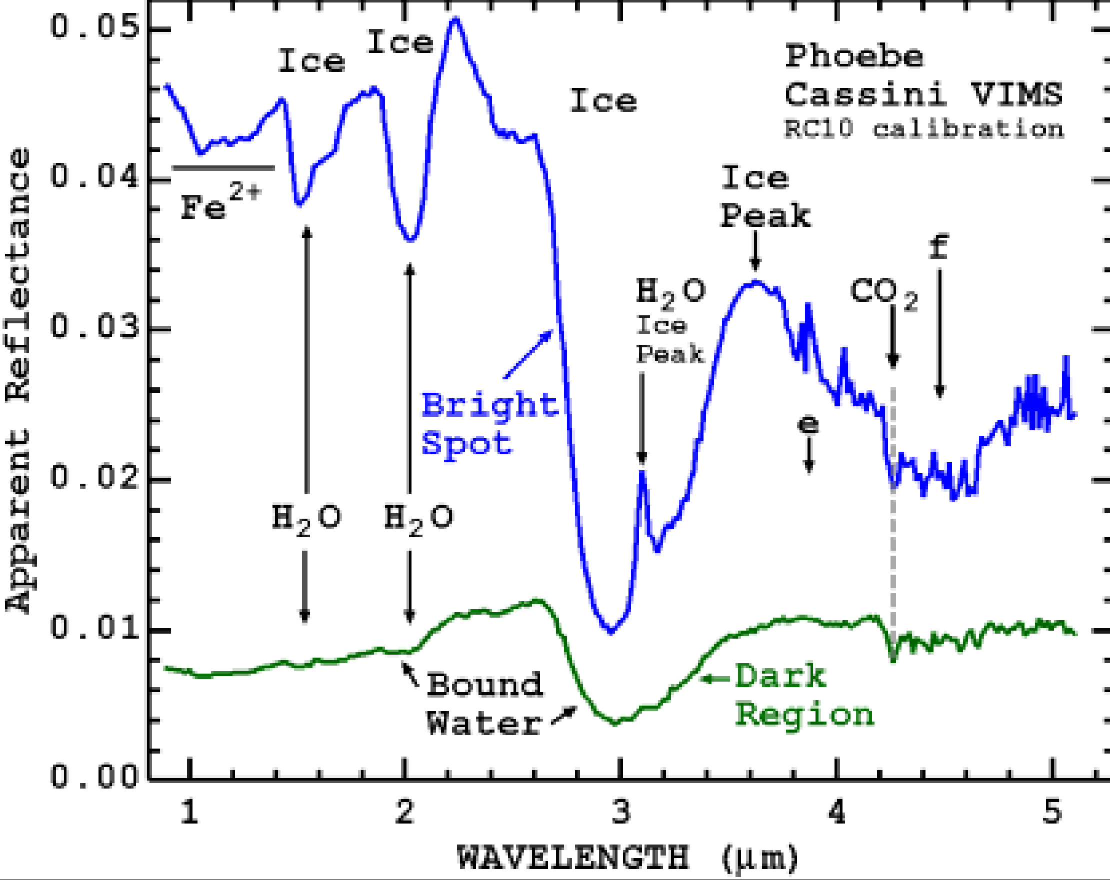
- Liquid water has been present on Earth since $\geq$ 4.3 billion yrs ago

- Mass of water in our ocean is 1.5 x 10^{24}g or 2 x $10^{-4}M_{Earth} \equiv 1$ *ocean*

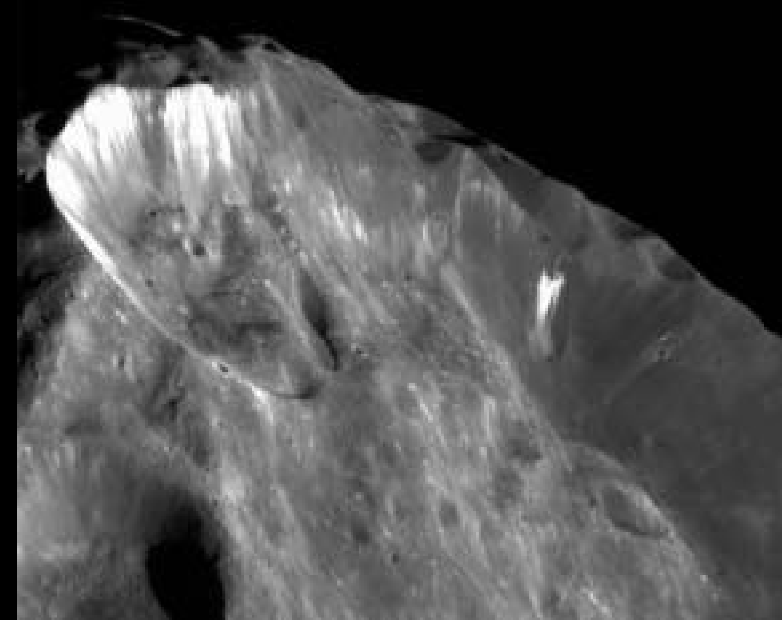
- Estimated mass of water in the mantle: 0.5-4 oceans

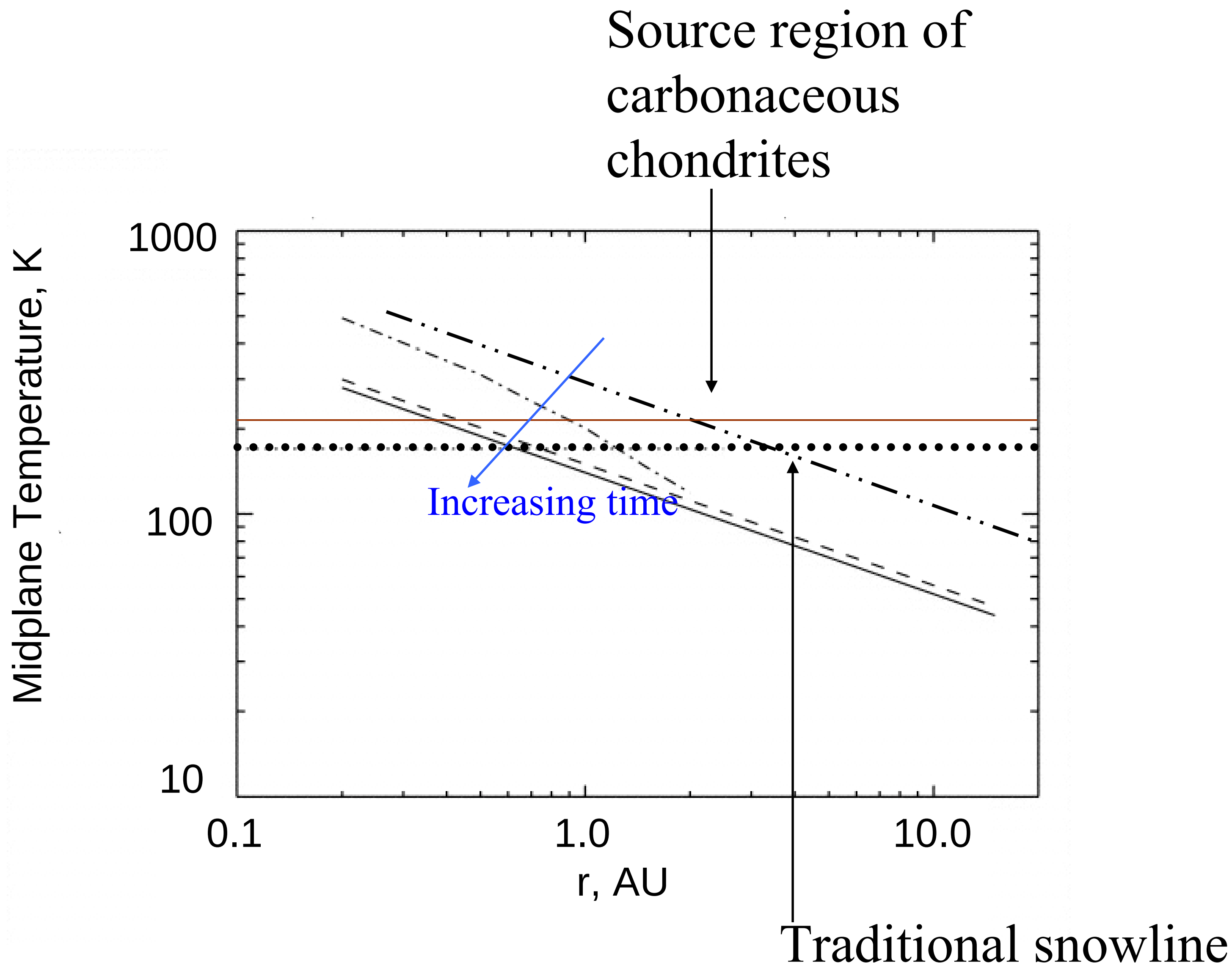
- Some argue for up to 50 oceans of water in primitive Earth



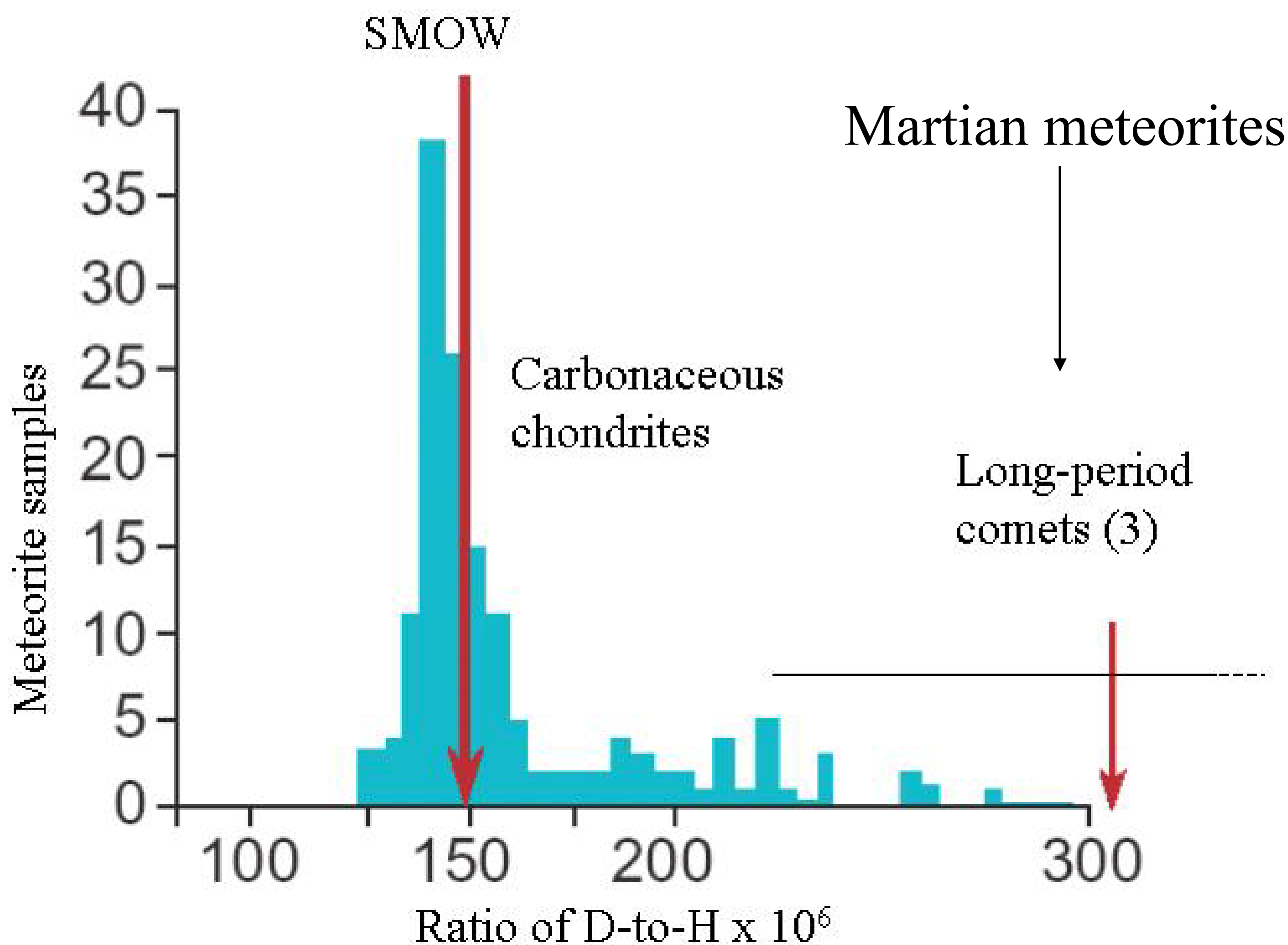


Saturn's Phoebe—example of a water-rich object from beyond the snowline

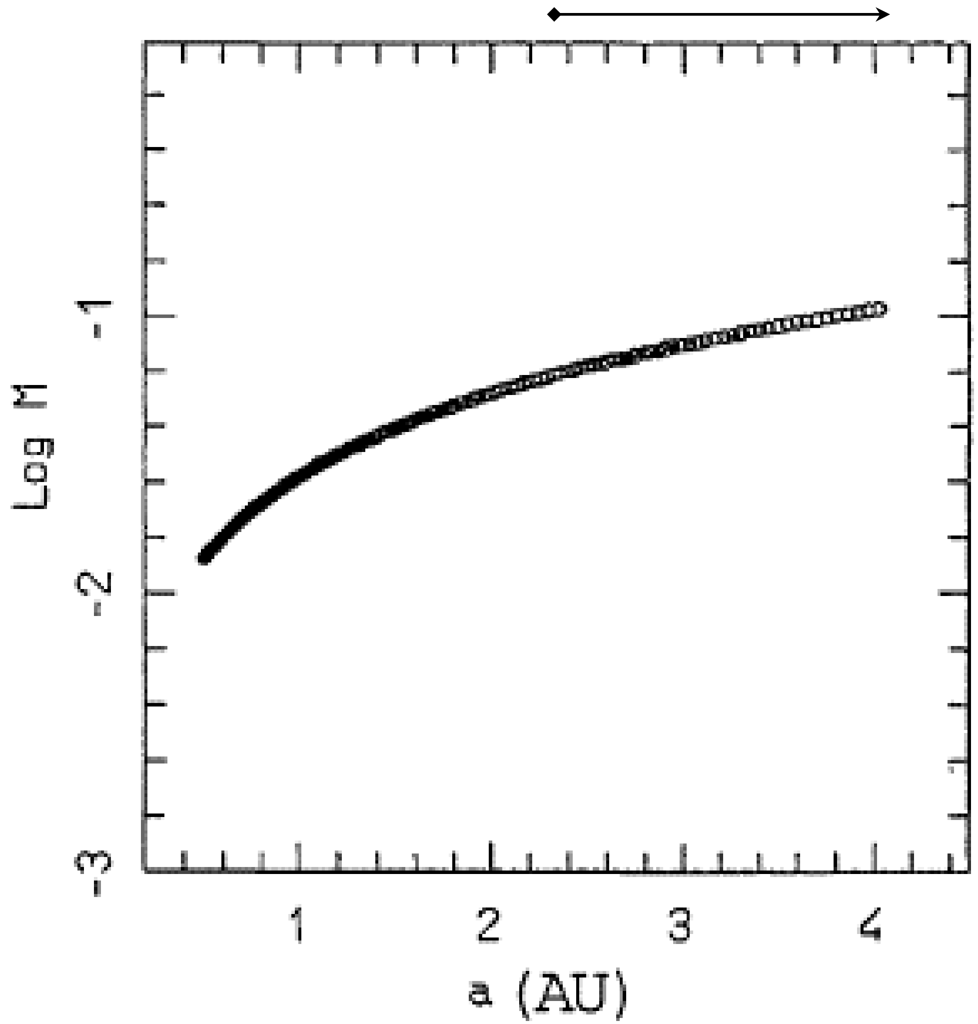




Sun’s protoplanetary disk


SMOW
Martian meteorites
Carbonaceous
chondrites
Long-period
comets (3)
Meteorite samples
0
5
10
15
20
25
30
35
40
100
150
200
300
Ratio of D-to-H x 10^6

carbonaceous chondrites



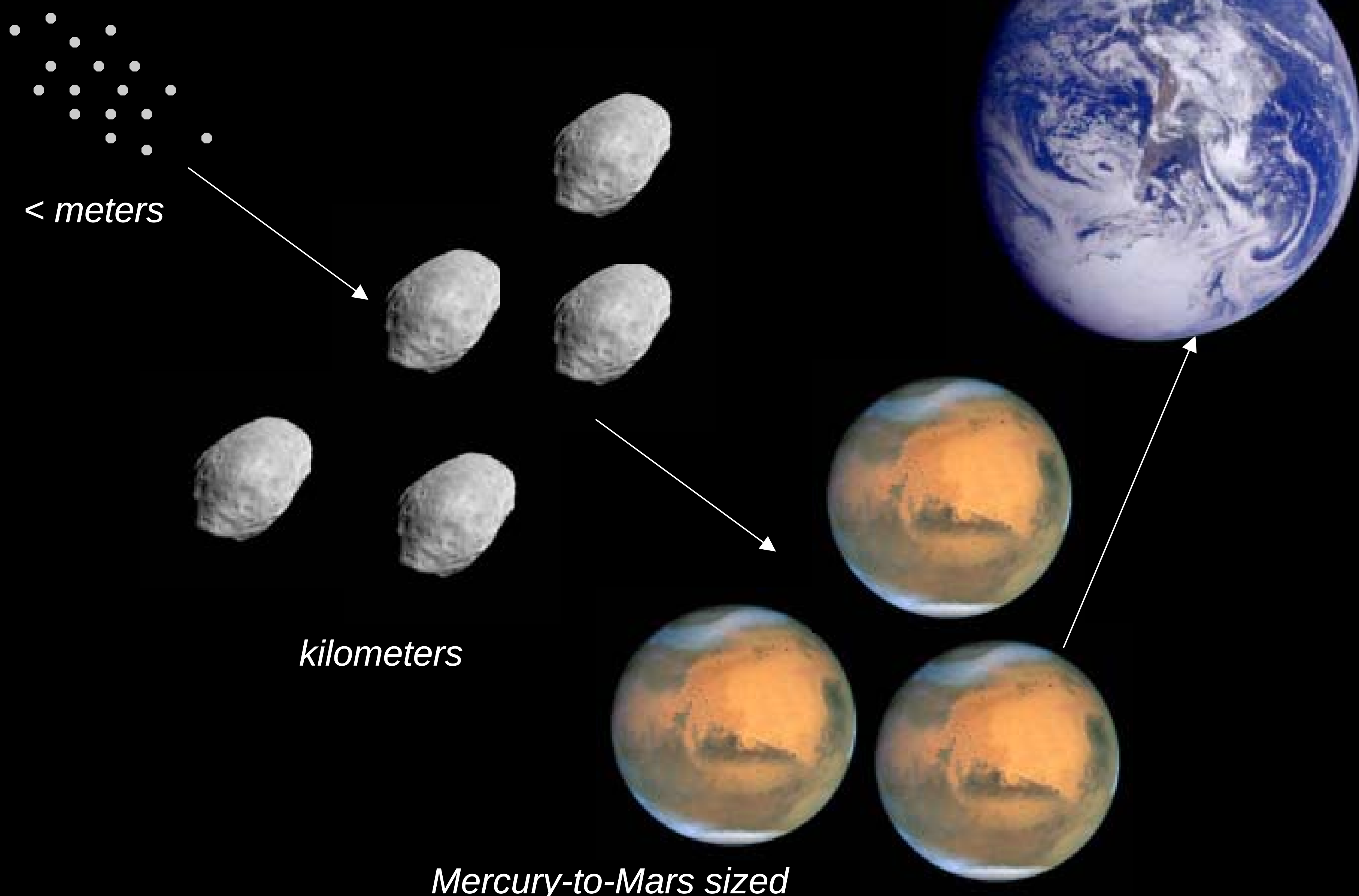
Asteroid belt mass today

Hypothesis: The primordial asteroid belt contained three orders of magnitude more material than it does today

Sources of water

- Planetesimals at 1 AU: Requires a cold nebula or adsorption of water onto grains prior to growth
- Planetary embryos at 1 AU: Same, and Moon was dry
- Comets, Phoebes: D/H in comets does not match that in Earth's oceans
- Snowline (low D/H) comets: none known (yet)
- Planet migrated inward: OK, but no mechanism post-gas
- Asteroids: Must be carbonaceous to be wet; limit 1-3% M_E; not enough in the present belt
- Embryos in primordial asteroid belt: Inferred, and same limit on mass

In the beginning there were planetesimals…



Symplectic integrator—the basic tool for tracking the evolution of large bodies

--Chambers, *MRAS* **304**, 793 (1999); *AJ* ***126***, 1119 (2003)--

- Sympl integ designed to solve Hamilton's eqns for N bodies:

$$\frac{dx_i}{dt} = \frac{\partial H}{\partial p_i}, \quad \frac{dp_i}{dt} = -\frac{\partial H}{\partial x_i}$$

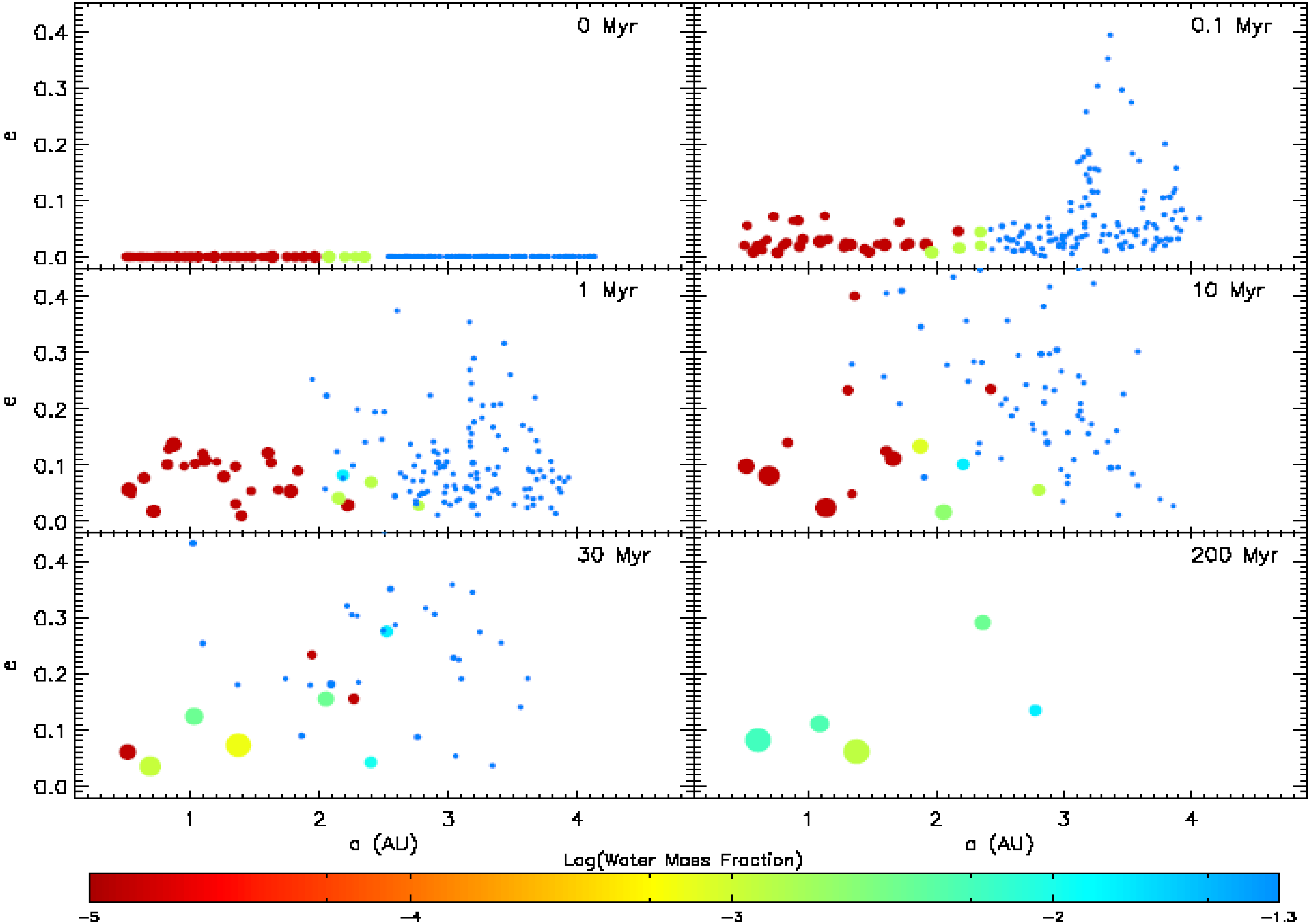
x_i, p_i the position and momentum of i;
H the system Hamiltonian

Any quantity q can be expressed as $dq/dt = \{q,H\} = Fq$; {}=poisson brackets; hence

$$q(t+\tau) = e^{\tau F} q(t)$$

In practice, divide the Hamiltonian into pieces (e.g., $H=H_A+H_B$) so that $q(t+\tau) = e^{\tau A}\, e^{\tau B}\, q(t);$ where A,B are the "F" operators corres to H_A, H_B
e.g.;
H_A : each body moves on unperturbed Kepler orbit around Sun;
H_B : each body is fixed but accelerated by perturbations due to other bodies.

Symplectic integrators conserve energy well over long *t* and are very fast for problems involving a large central body.



Yellow planets have ~Earth water content

• In many simulations, the Earth accretes at least one large planet from the asteroid belt. ***Jupiter is essential for generating large planets and stirring orbits.***

•10% or less of the Earth's mass is of main belt origin. 5% or less of the Earth's mass is from the water-rich outer belt.

•Planets formed in the asteroid belt are added throughout the accretion process, and can provide 3-5 oceans worth of water--with D/H ~ SMOW.

Part II. Sources for Mars

- In all of the (gas-free) simulations analyzed, the body at ~1.5 AU is struck by a big water-rich embryo-- but the final planet size is too big to be Mars.

- So Mars apparently was not struck by such an embryo--a less likely but not improbable outcome.

- Then most or all of Mars' water is from small asteroids and comets. We calculate the probability of impact of smaller asteroids and of the comets on Mars during/after its formation.

- These calculations lead to an amount of water added to Mars between 0.06-0.27oceans.

Part III: Extrasolar

Planetary accretion is a stochastic process, since much of the mass were contained in a small number of large bodies.

If bodies formed in the asteroid belt, each of the inner planets could have been hit by a different number N of embryos (N=0,1,2,3,...).

What might this say about the diversity of architectures of planetary systems?

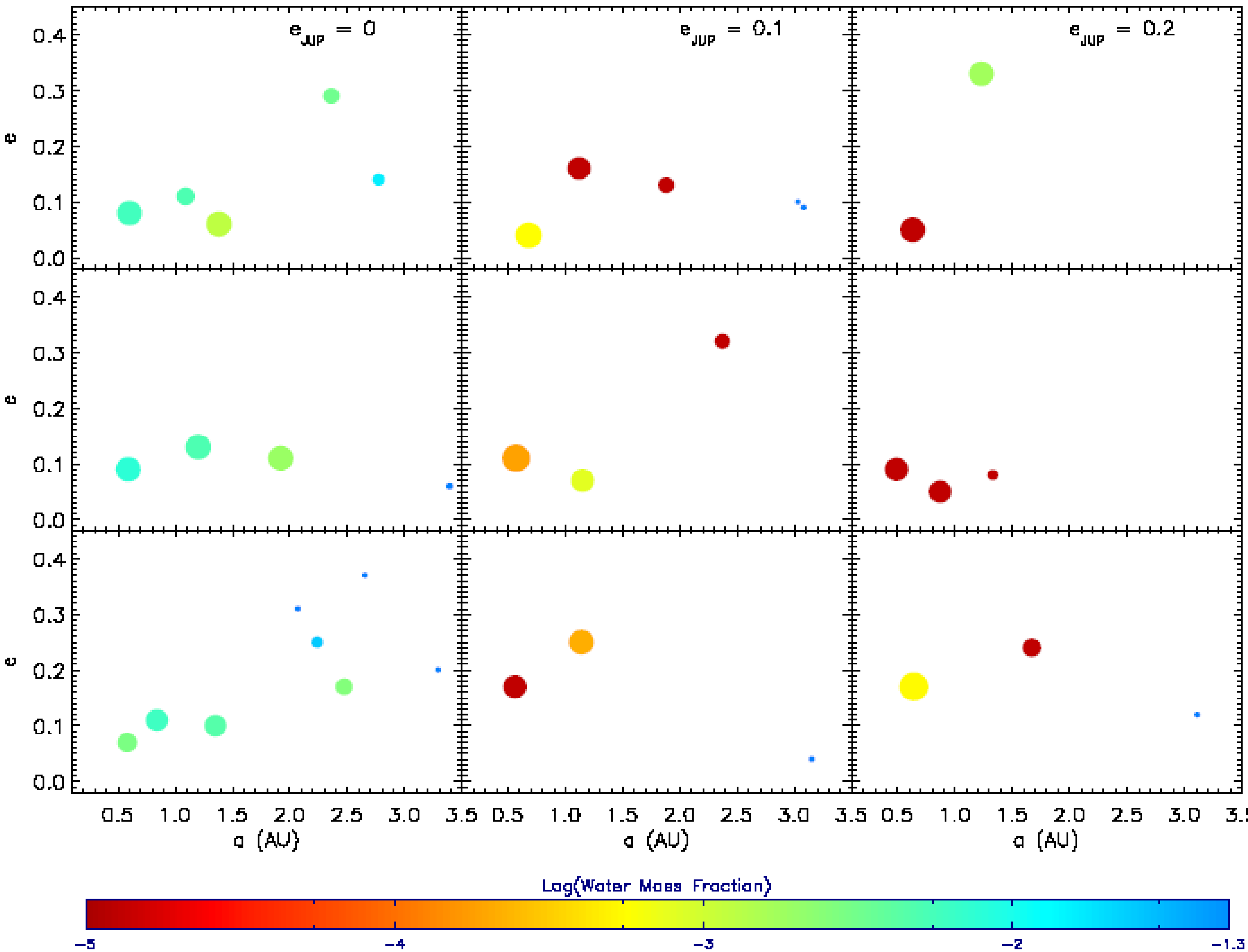
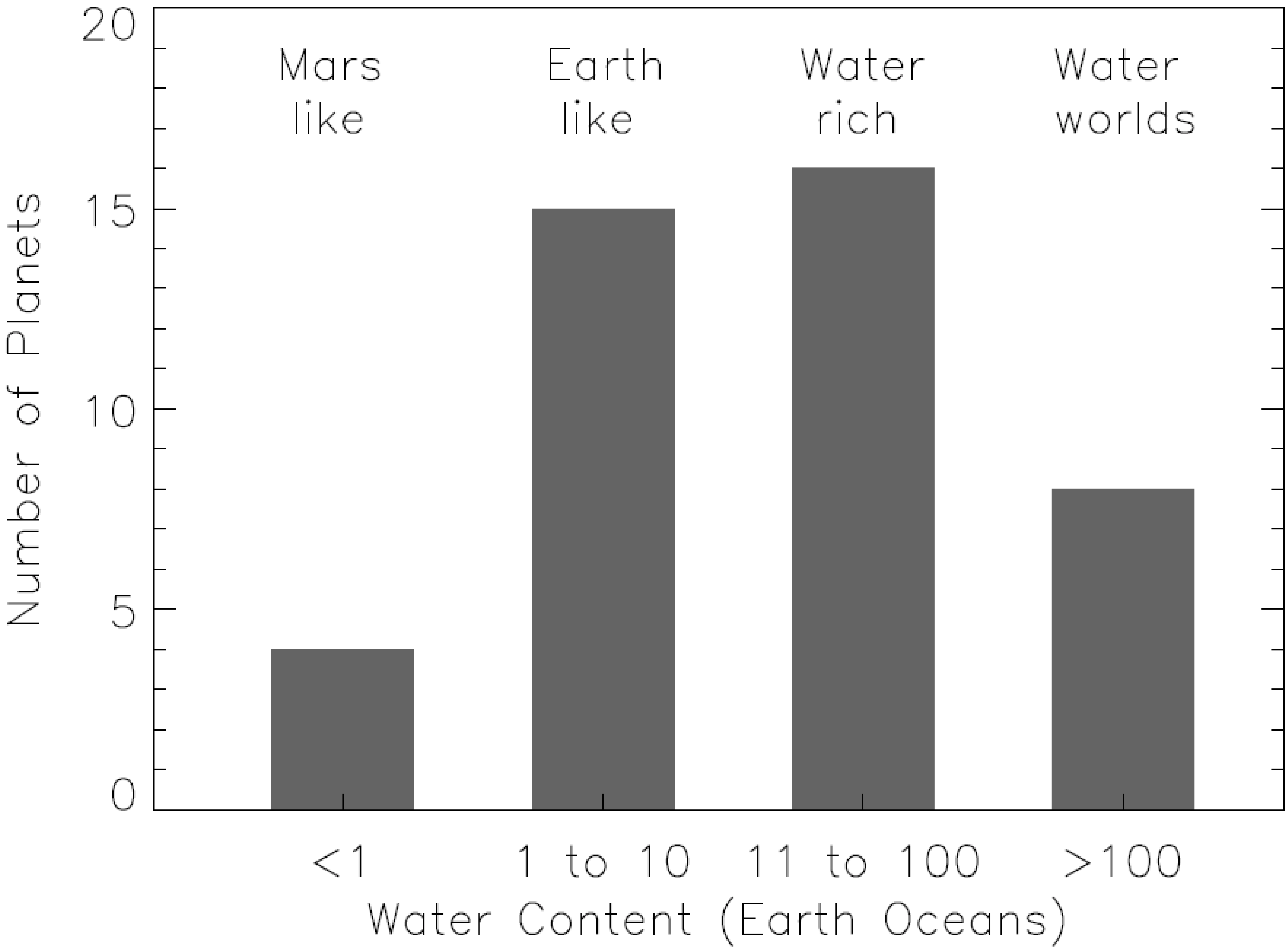
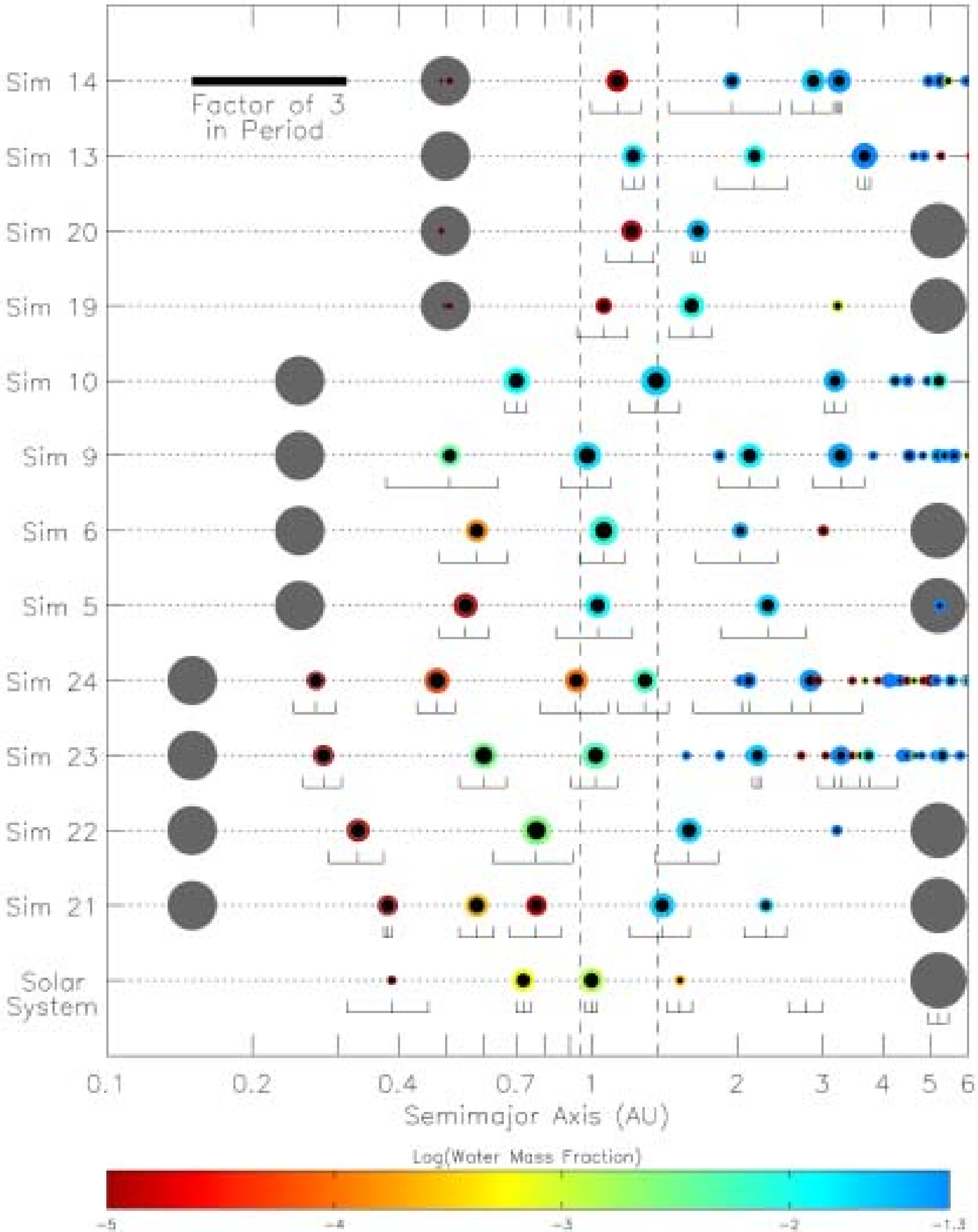


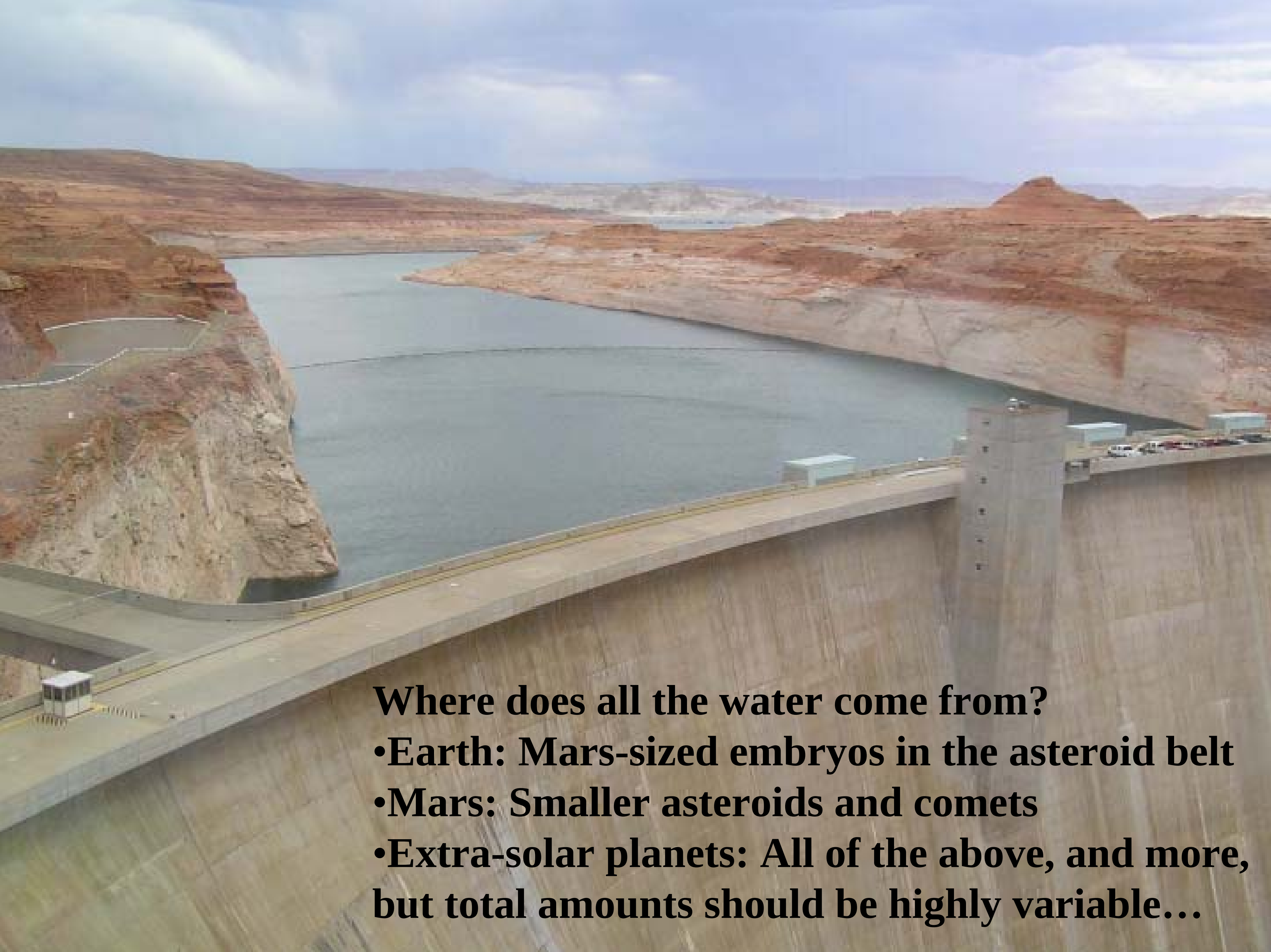
Fig. 6.— The final configuration of nine planetary systems with identical initial conditions (a_J = 5.2 AU, $M_J = M_{J,r}$, $M_{planetesimal} = 0.01\ M_\oplus$) apart from Jupiter's initial eccentricity, which is the same for all simulations in a given column. Note the dramatic decline in volatile content for e_J greater than zero.


Mars like
Earth like
Water rich
Water worlds
0
5
10
15
20
Number of Planets
<1
1 to 10
11 to 100
>100
Water Content (Earth Oceans)



Simulations by Raymond et al. in the presence of hot Jupiters.

Again, a "yellow" planet has Earth water content



Where does all the water come from?

- **Earth: Mars-sized embryos in the asteroid belt**
- **Mars: Smaller asteroids and comets**
- **Extra-solar planets: All of the above, and more, but total amounts should be highly variable…**